Fuel Cell Technologies Office

American Energy & Manufacturing Competitiveness Partnership

http://www.aemcsummit.compete.org/

Fuel Cell Manufacturing

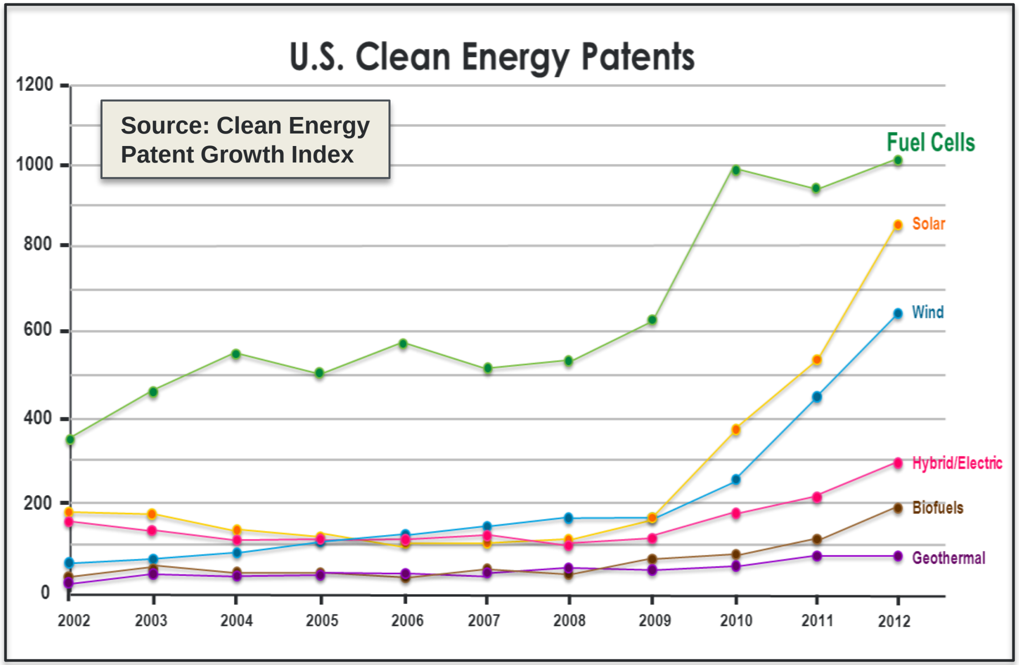
Dr. Sunita Satyapal
Director, Fuel Cell Technologies Office
Dr. Nancy Garland
Technology Development Manager, Manufacturing R&D, Fuel Cell Technologies Office

The Future of Fuel Cell Manufacturing Panel Session

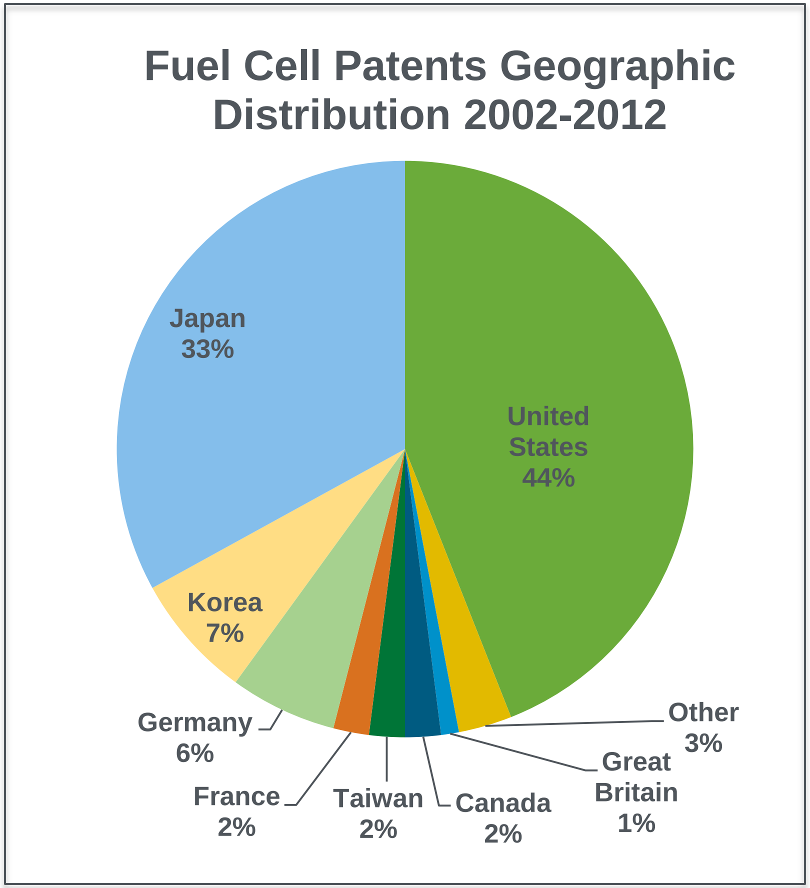
- Federal program: DOE Fuel Cell Technologies Office
- National trade association: Fuel Cell & Hydrogen Energy Association
- State Coalition Example: Ohio Fuel Cell Coalition

Fuel Cells – An Emerging Global Industry

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



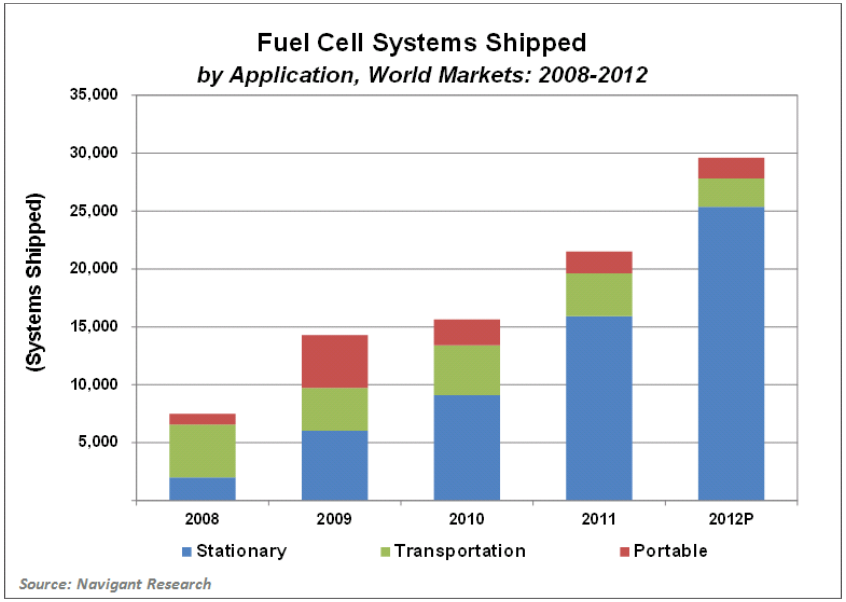
Top 10 companies for fuel cell patents: GM, Honda, Toyota, Samsung, UTC Power, Nissan, Ballard, Panasonic, Plug Power, Delphi Technologies

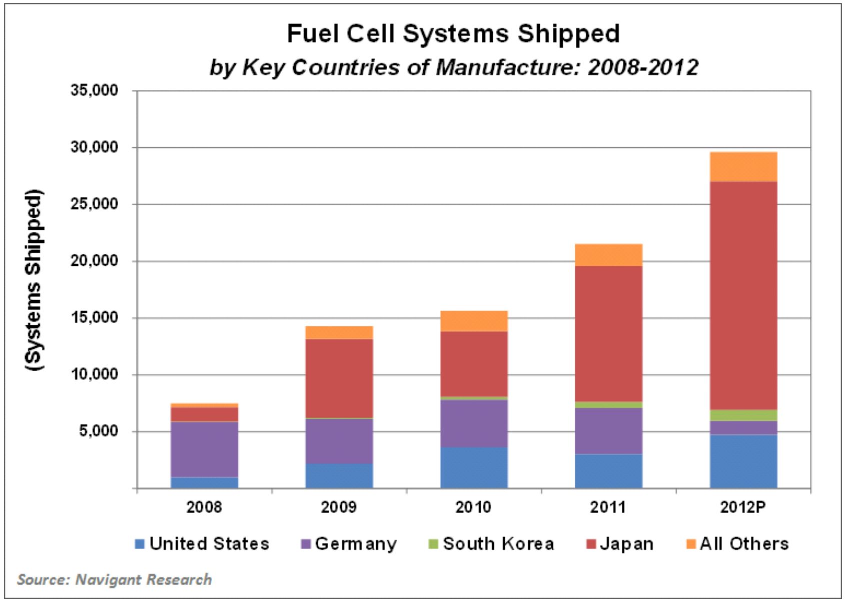


- Clean Energy Patent Growth Index[1] shows growth in all clean energy technology patents
- More than 1,000 fuel cell patents issued in 2012

[1] http://cepgi.typepad.com/heslin_rothenberg_farley_/2013/03/clean-energy-patent-growth-index-2011-year-in-review.html

Fuel Cell Market Overview





Market Growth

Fuel cell markets continue to grow

48% increase in global MWs shipped

62% increase in North American systems shipped in the last year

The Market Potential

Independent analyses show global markets could mature over the next 10–20 years, with potential for revenues of:

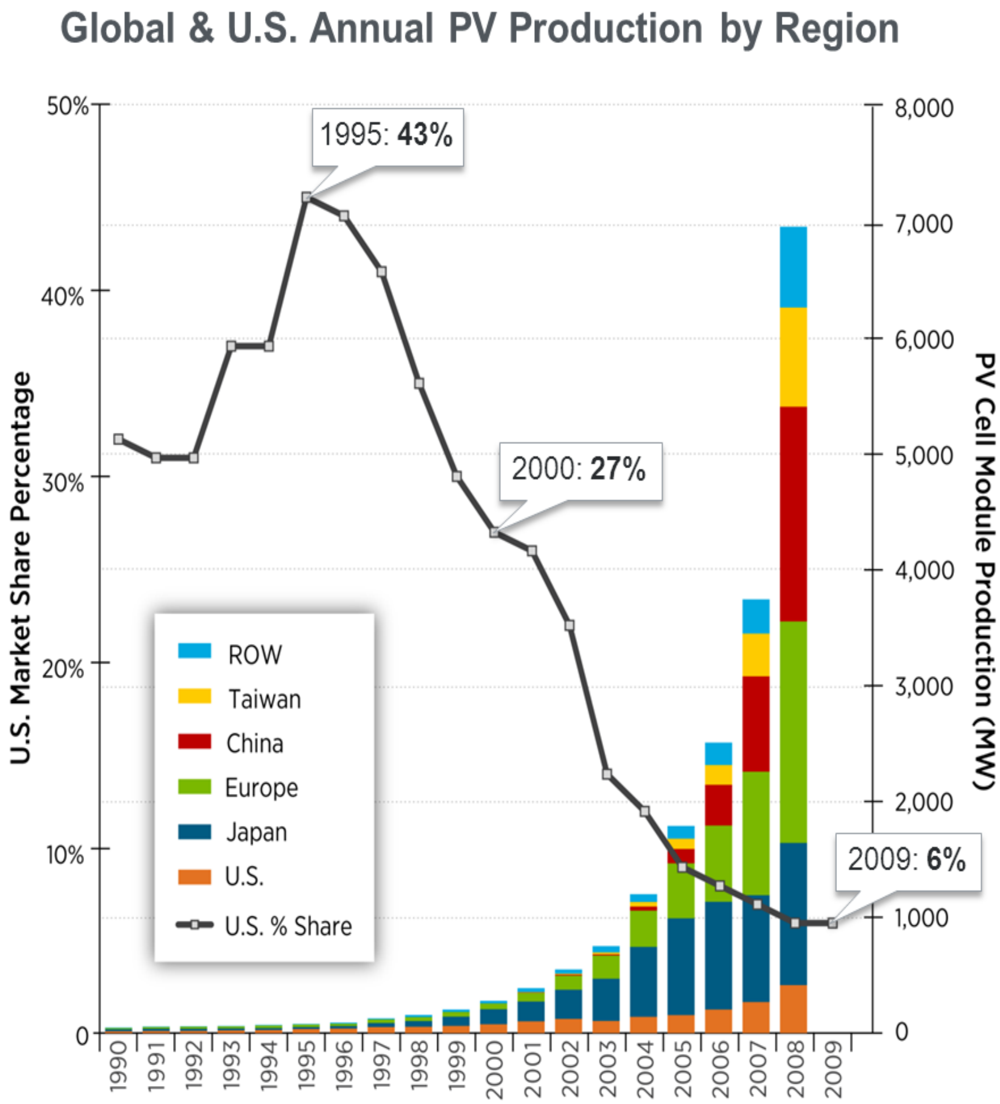
- **$14 – $31 billion/year for stationary power**
- **$11 billion/year for portable power**
- **$18 – $97 billion/year for transportation**

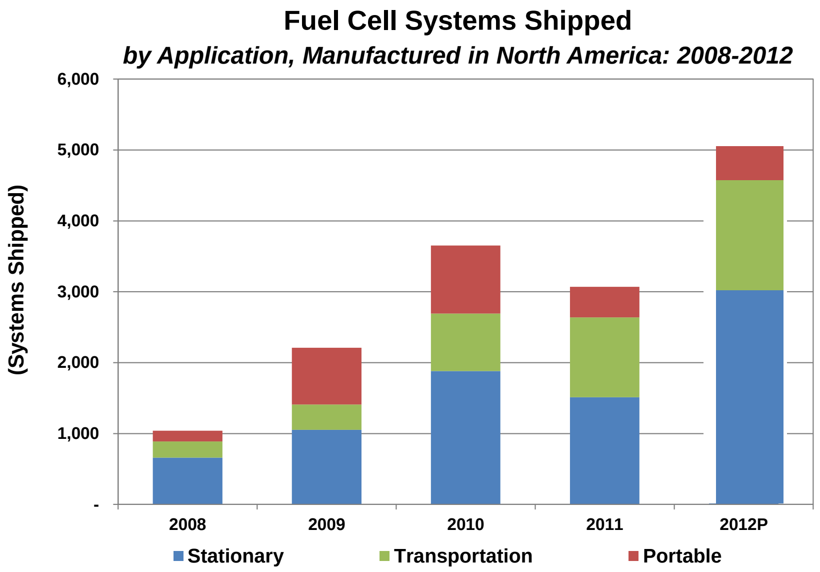
The global hydrogen market is also robust with over 55 Mtons produced in 2011 and over 70 Mtons projected in 2016, a > 30% increase.

Several automakers have announced commercial FCEVs in the 2015-2017 timeframe.

For further details and sources see: *DOE Hydrogen and Fuel Cells Program Plan*, http://www.hydrogen.energy.gov/pdfs/program_plan2011.pdf; FuelCells 2000, Fuel Cell Today, Navigant Research, Markets & Markets

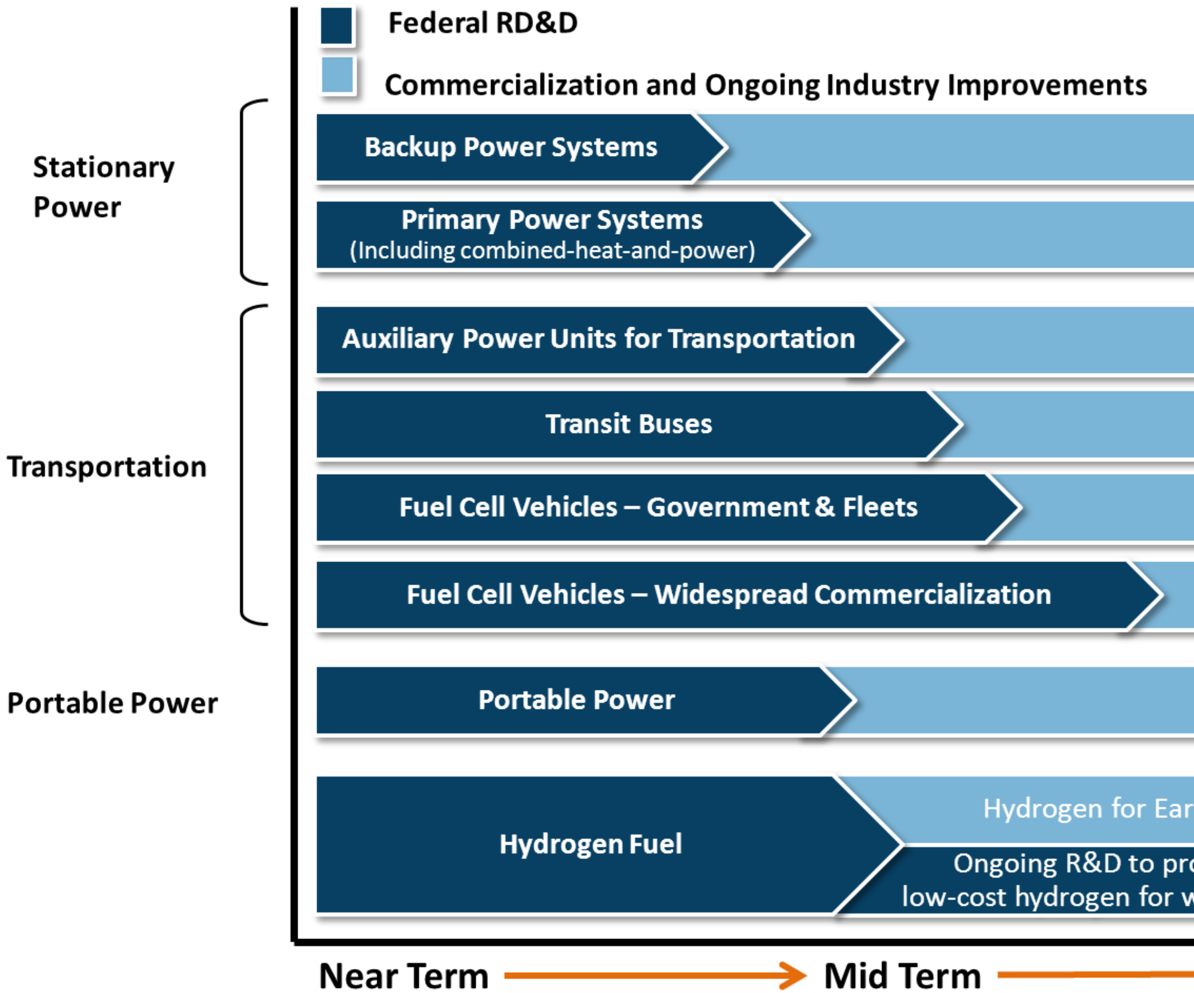
Fuel Cells- an emerging technology
Can we apply lessons learned from Solar?





Still early for fuel cells- Need comprehensive strategy to enable U.S. leadership in emerging technology- balance near, mid and long-term RDD&D

Mission: Enable widespread commercialization of a portfolio of hydrogen and fuel cell technologies through applied research, technology development and demonstration, and diverse efforts to overcome institutional and market challenges.



Fuel Cell Type	Cost & Durability Status	Cost & Durability Target
Medium scale CHP (natural gas)	\$2,500-4,500/kW 40,000-80,000 h	\$1,000/kW 80,000 h
Micro CHP (5 kW systems)	\$2,300-4,000/kW 12,000 h	\$1,500/kW 60,000 h
APUs (1-10 kW, system)	\$2,000/kW 3,000 h	\$1,000/kW 20,000 h
Buses	\$2,000,000 12,000 h	\$600,000 25,000 h
Automotive	~\$55/kW* 2,500 h (on road) 4,000 h (lab proj.)	\$30/kW* (\$40/kW by 2020) 5,000 h
Portable Power (100-250 W)	\$15/W 2,000 h	\$5/W 5,000 h

*Projected cost assuming manufacturing volumes of 500,000 units/yr

Opportunities for Distributed Generation (DG) and Efficient use of Natural Gas and Biogas

Critical Loads- e.g. banks, hospitals, data centers

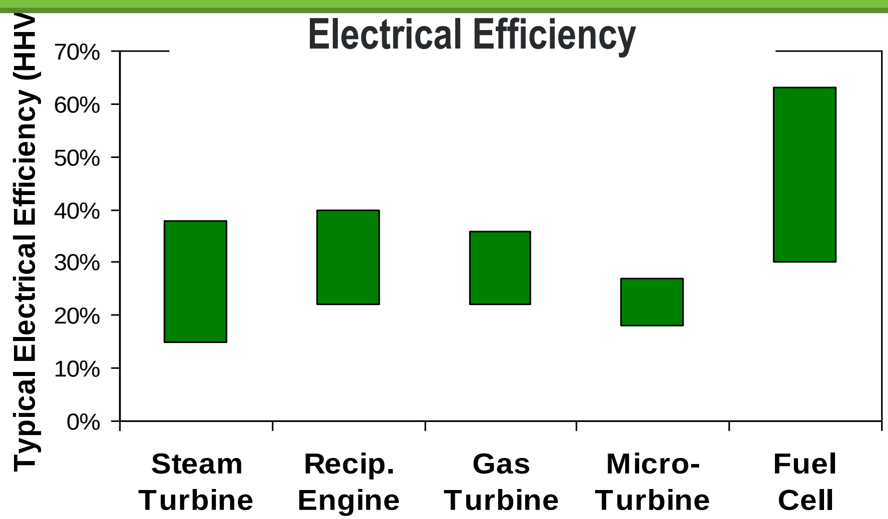
Supermarkets *one of several in the food industry interested*

New World Trade Center will use ***12 fuel cells totaling 4.8MW***

During Hurricane Sandy, fuel cells were instrumental in providing backup power for many in NY, NJ, and CT.

- >60 fuel cells acted as backup power for cell phone towers.
- >20 fuel cells systems provided continuous power to buildings

Range of electrical efficiencies for DG technologies



Source: EPA, Catalog of CHP Technologies, December 2008

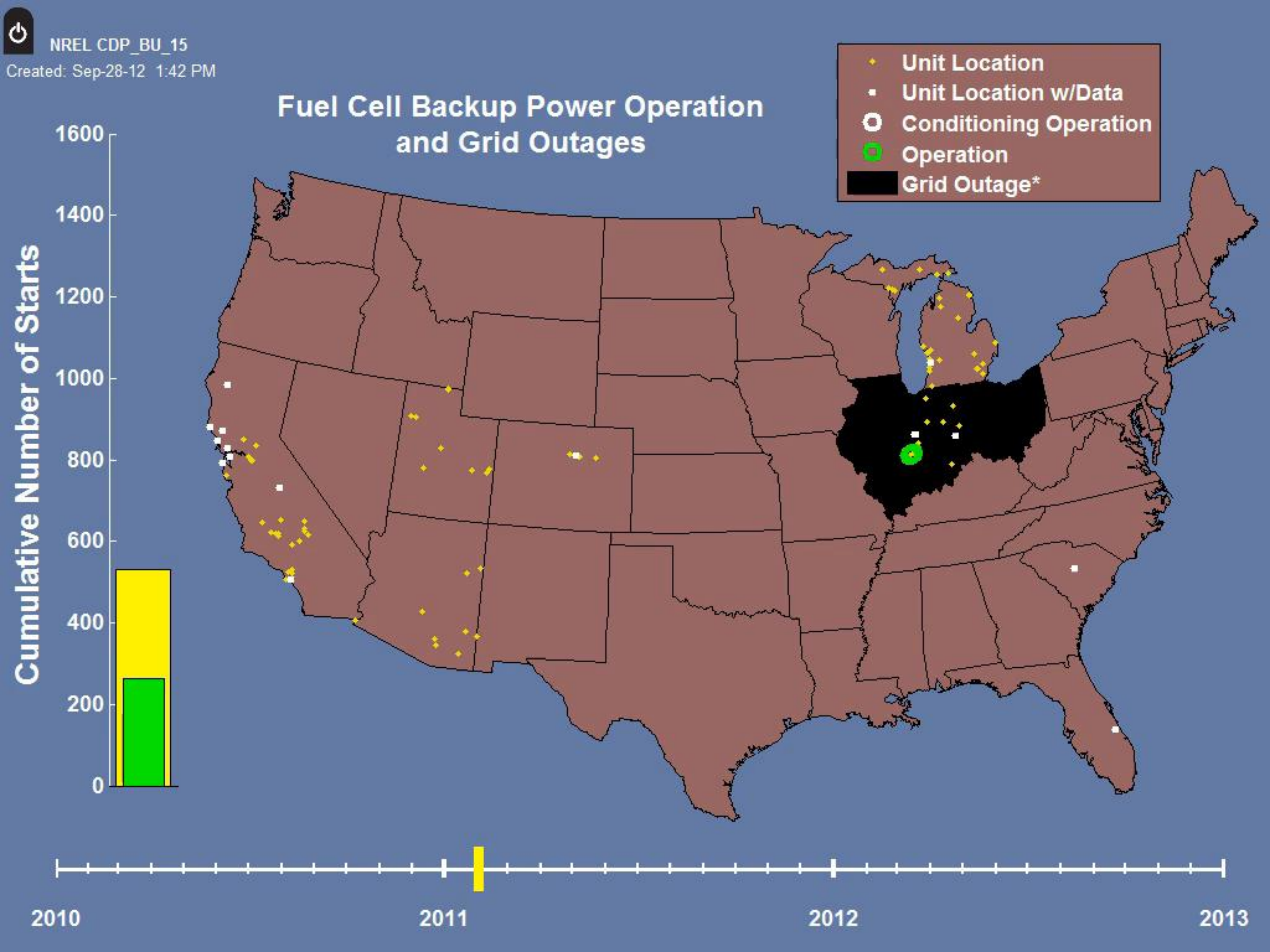
Putting fuel cells to the test…

Hurricane Sandy was the largest Atlantic hurricane on record.

Winds spanning more than 1,100 miles

>>$60 billion in damages

Fuel cells demonstrated the ability to provide reliable power in numerous examples



NREL CDP_BU_15
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Fuel Cell Backup Power Operation
and Grid Outages
Unit Location
Unit Location w/Data
Conditioning Operation
Operation
Grid Outage*
Cumulative Number of Starts
1600
1400
1200
1000
800
600
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2010
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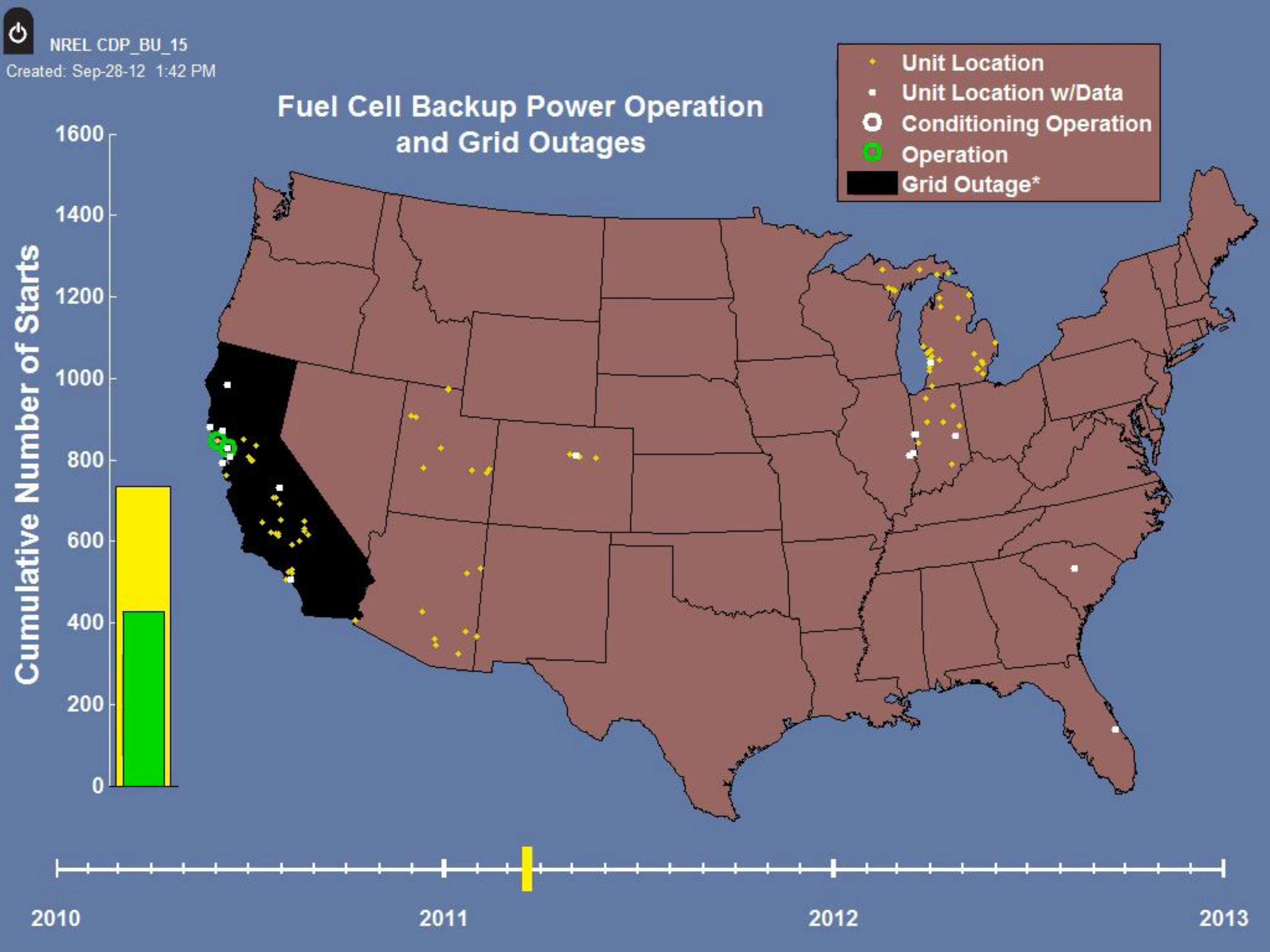
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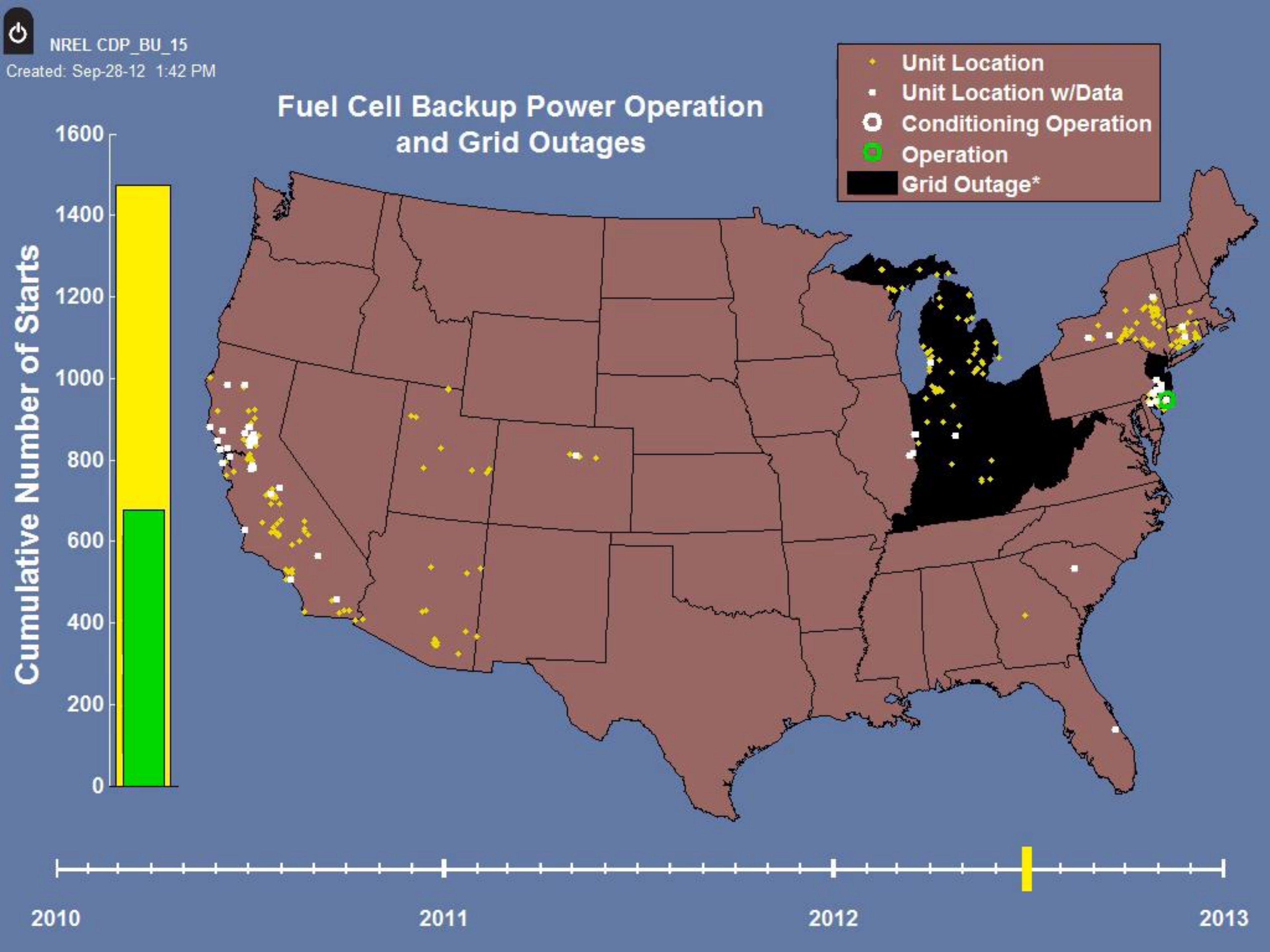

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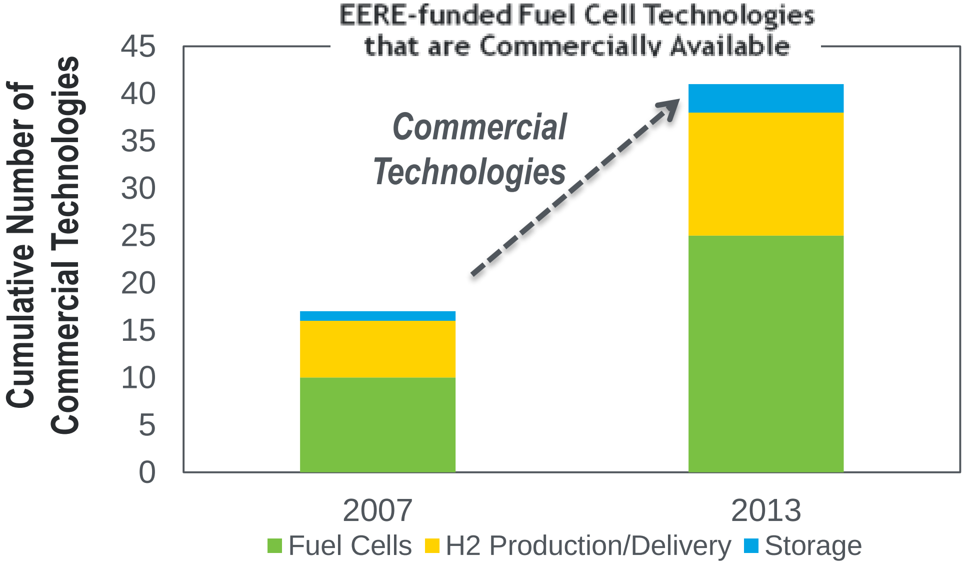
Assessing the Impact of DOE Funding

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

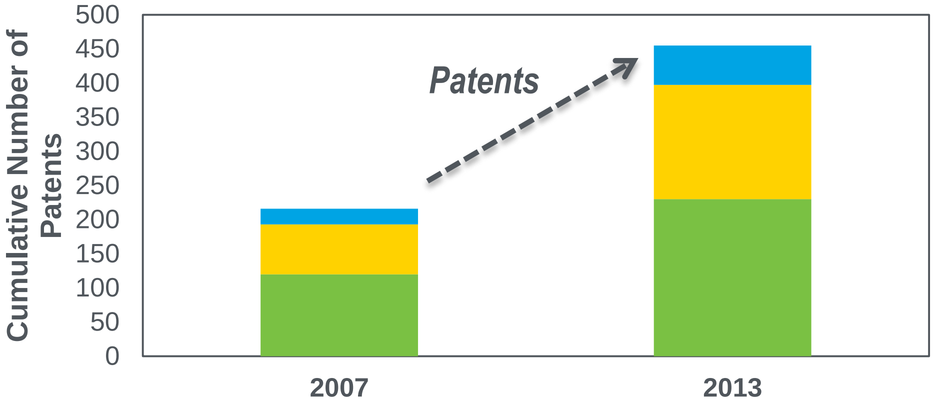
DOE funding has led to 40 commercial hydrogen and fuel cell technologies and 65 emerging technologies.

Accelerating Commercialization



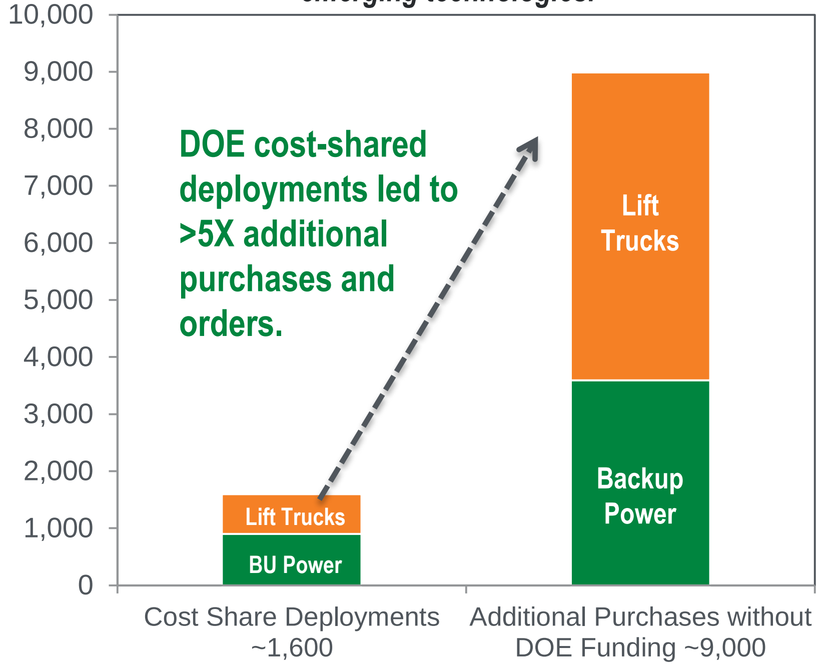
Source: Pacific Northwest National Laboratory

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pathways_success_hfcit.pdf



Leveraging DOE Funds:

Government as "catalyst" for market success of emerging technologies.



More than 450 PATENTS resulting from EERE-funded R&D:

- ***Includes technologies for hydrogen production and delivery, hydrogen storage, and fuel cells***

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pathways_2013.pdf

Fuel cells in the spotlight- examples

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

President Obama inspects a fuel cartridge while at the Swedish Royal Institute of Technology.

Business case is emerging for fuel cell forklifts and ground support equipment

Fuel cells in the spotlight- examples

Hydrogen fuel cell powers lights at entertainment industry events.

Hydrogen fuel cell powered light tower at Space Shuttle launch

Co-Launched H_2USA Public-Private Partnership – May 2013

H_2USA

Mission: To promote the commercial introduction and widespread adoption of FCEVs across America through creation of a public-private partnership to overcome the hurdle of establishing hydrogen infrastructure.

More than 25 Partners

Current partners include (additional in process):

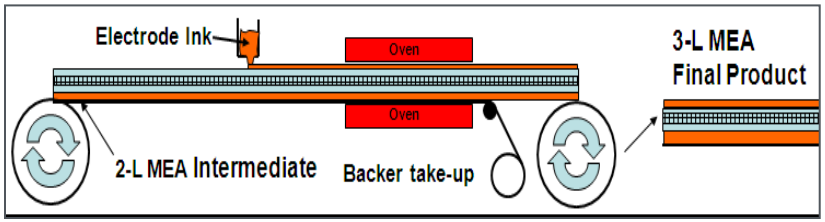
- U.S. DEPARTMENT OF ENERGY
- Fuel Cell & Hydrogen Energy Association
- Global Automakers
- EDTA Electric Drive Transportation Association
- DAIMLER
- HYDROGENICS Advanced Hydrogen Solutions
- HONDA The Power of Dreams
- NISSAN
- HYUNDAI
- GM
- Mercedes-Benz
- Oak Ridge National Laboratory
- AGA American Gas Association
- ITM POWER Energy Storage | Clean Fuel
- California Fuel Cell Partnership DRIVING FOR THE FUTURE
- SCRA
- Sandia National Laboratories
- PROTON THE LEADER IN ON SITE GAS GENERATION.
- NREL NATIONAL RENEWABLE ENERGY LABORATORY
- AIR LIQUIDE
- arc:HYDROGEN
- plug power
- NUVERA Making hydrogen make sense.
- Massachusetts Hydrogen Coalition
- TOYOTA
- Argonne NATIONAL LABORATORY

Manufacturing R&D—Overview and Highlights

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

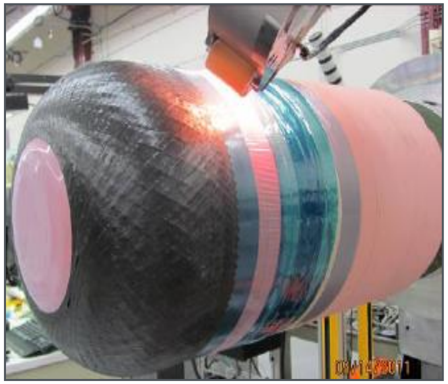
Goal: Research and develop technologies and processes that reduce the cost of manufacturing hydrogen production, delivery, storage, and fuel cell systems.

Roll-to-Roll MEA Processing at W.L. Gore



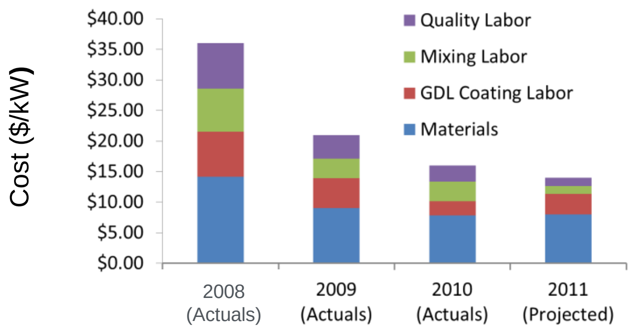
- Increase MEA performance
- Eliminate intermediate backing material
- Reduce number of coating passes
- Direct coating of catalyst onto ionomer

Tank Manufacturing at Quantum Technologies



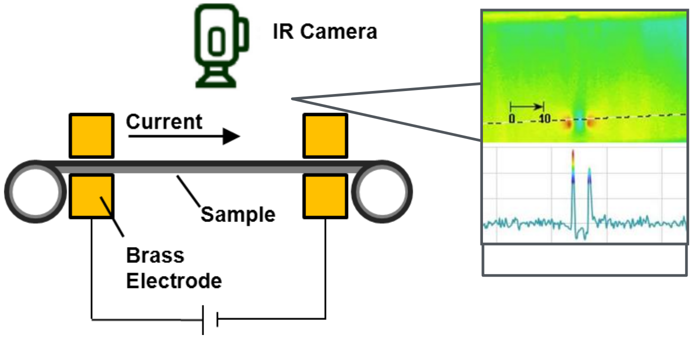
- Reduced carbon fiber use while maintaining structural integrity
- Integrate new, low-cost, composite fiber
- Increase manufacturing efficiency

Optimized Fabrication of GDLs at Ballard



- Demonstrated 4x increase in production capacity and >50% decrease in GDL cost
- Improved production yields and efficiency
- Move to full width production

In-Line Diagnostics Techniques at NREL



- Developing in-line diagnostic techniques for MEA component quality control
- Investigating effects of manufacturing defects on MEA performance

- Held 8/11 in Washington, D.C. with representatives from industry, academia, lab, and government
- **Identified and prioritized needs and barriers to manufacturing**
- Outputs support potential FY13 FOA for H_2 & FC Manufacturing R&D

Issue	Votes
PEM Fuel Cells/Electrolyzers BOP: Facilitate a manufacturing group for DOE to expand supply chain.	21
Electrodes: How to apply ink directly to membrane; dual direct coating of CCM; *membrane dimensional change with deposition of current inks (Fuel cell R&D)*	20
PEM Fuel Cells/Electrolyzers BOP: Develop low cost manufacturing of natural gas reformers (Fuel cell R&D)	18
Stack Assembly: High volume stack assembly processes: reduced labor, improved automation	15
Quality/Inspection/Process Control: Develop methods of identifying coating defects on a moving web, then rejecting single pieces downstream; defect detection after MEA assembly when defect may no longer be visible; ability to separate materials with defects from rolled goods with minimum production of scrap	15
SOFC: Multi-layer/component sintering	14

http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_h2_fc_manufacturing.html

Thank You

American Energy & Manufacturing Competitiveness Partnership

http://www.aemcsummit.compete.org/

Sunita.Satyapal@ee.doe.gov

hydrogenandfuelcells.energy.gov

Additional Information

The Big Picture

Fuel cell vehicles per year (10% of world market in 2030)	**15 million**
MEAs per year (300 MEAs/stack)	4.5 billion
Manufacturing operation	8000 hrs/yr, 80% up-time
MEA production rate	11,700 MEAs/minute
Line speed (assuming 20 production lines)	20 meters/min
Quality requirement (MEAs) for 0.1% stack failure	**1 critical MEA failure in 300,000 (this is approximately six sigma quality)**
Quality requirement (MEAs) for six sigma stack quality	**1 critical MEA failure in ~90 million (this is approximately "seven sigma")**

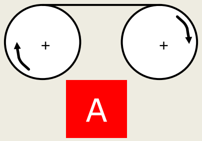
High speed manufacturing and quality will be critical!

Source: Debe, Nature, 486 (7 June 2012), pp. 43-51.

State-of-the-art MEA Manufacturing

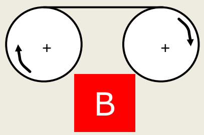
Step 1
Coat Cathode Catalyst Layer Roll-to-Roll on Intermediate Release Film

QC: Inline

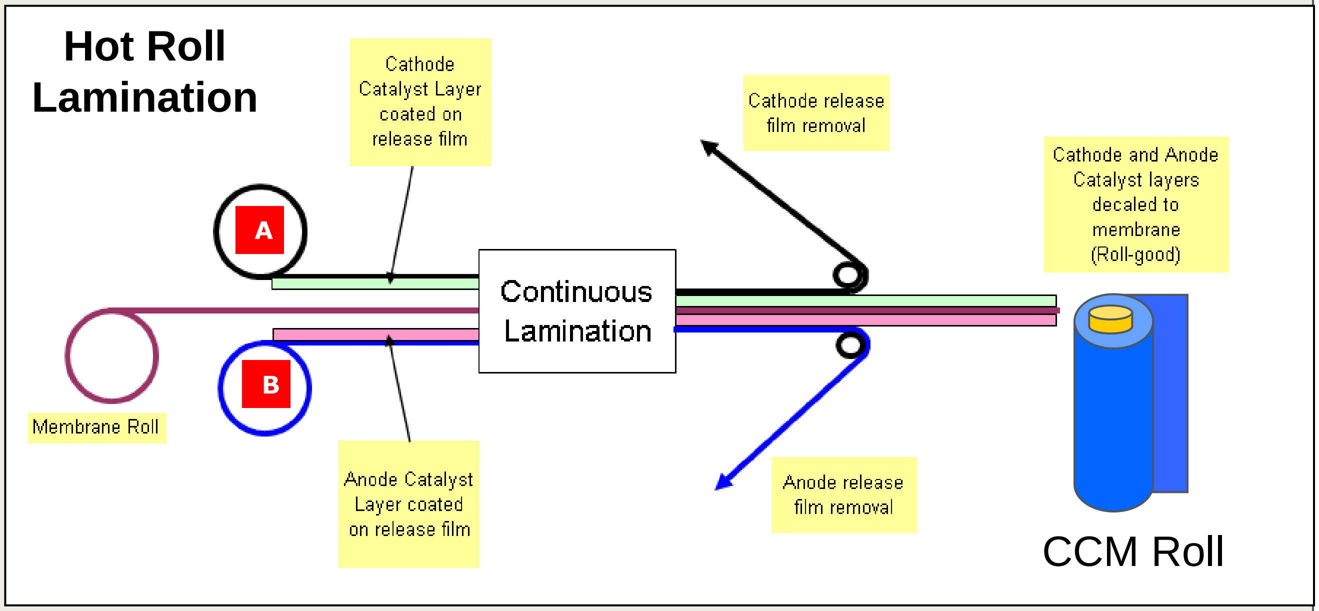


Step 2
Coat Anode Catalyst Layer Roll-to-Roll on Intermediate Release Film

QC: Inline



Step 3
Decal Transfer Cathode and Anode Catalyst Layers onto Membrane using Continuous Lamination Techniques



Total Pt loading typically 0.5 mg/cm^2

Understanding of critical design parameters and validated tolerance bands is ongoing thus tolerances are tight = strain on yields

Source: Ballard

Manufacturing R&D

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

We are developing and demonstrating technologies and processes to:

- **_Reduce cost of fuel cell components and systems, as well as components and systems for producing and storing hydrogen_**
- **_Grow domestic supplier base_**

Near-term Goal for Early Markets

Lower fuel cell stack manufacturing cost by $1000/kW (*from $3,000/kW to $2,000/kW, for low-volume manufacturing*)

This is the first time a scanning XRF has been used on GDEs – BASF

Project Emphasis

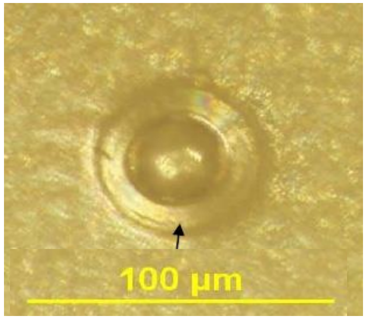
- **Electrode Deposition**
  - BASF, PNNL
- **High Pressure Storage**
  - Quantum Technologies
- **MEA Manufacturing**
  - Gore, LBNL, RPI
- **Gas Diffusion Layer (GDL) Fabrication**
  - Ballard
- **Effective Testing of Fuel Cell Stacks**
  - PNNL, UltraCell
- **Effective Measurement of Fuel Cell Stacks**
  - NREL, NIST

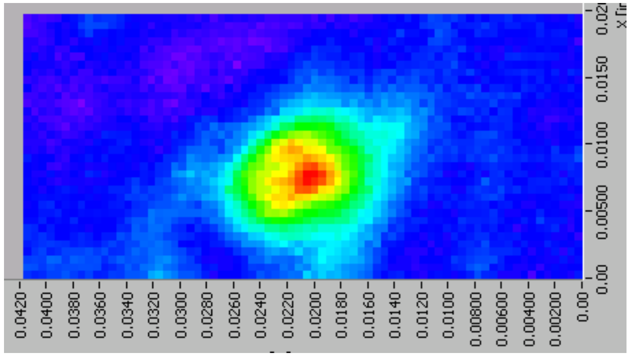
QC is critical!!!

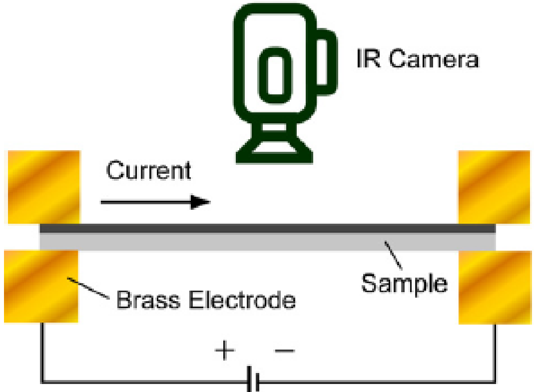
“Just four sequential process steps with 90% yields would increase costs by 30%...”*

Need MEA production rate of 11,700 MEAs/min @ 20 m/min

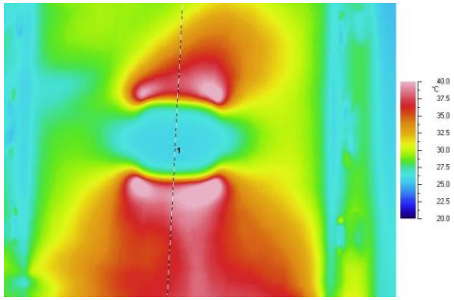
- Optical diagnostics for fuel cells developed at NREL for PV cell QC
- Bubble in fuel cell membrane detected using optical diagnostics







NREL
NATIONAL RENEWABLE ENERGY LABORATORY



- In-plane DC excitation/IR detection reveals bare spot in fuel cell electrode

The tools needed to find the bad stuff at speed are not all there!

*Debe, Nature, 486, 2012, pp. 43-51.

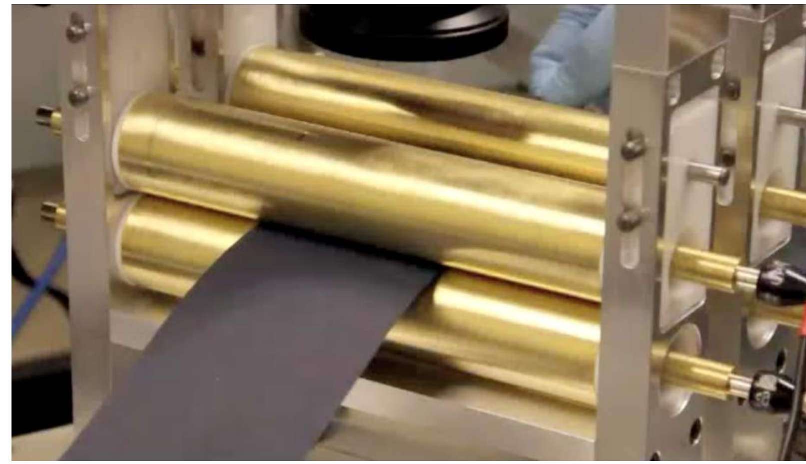
Progress - Manufacturing

Achieved areal image of catalyst layer uniformity

Developing in-line diagnostics for MEA component quality control

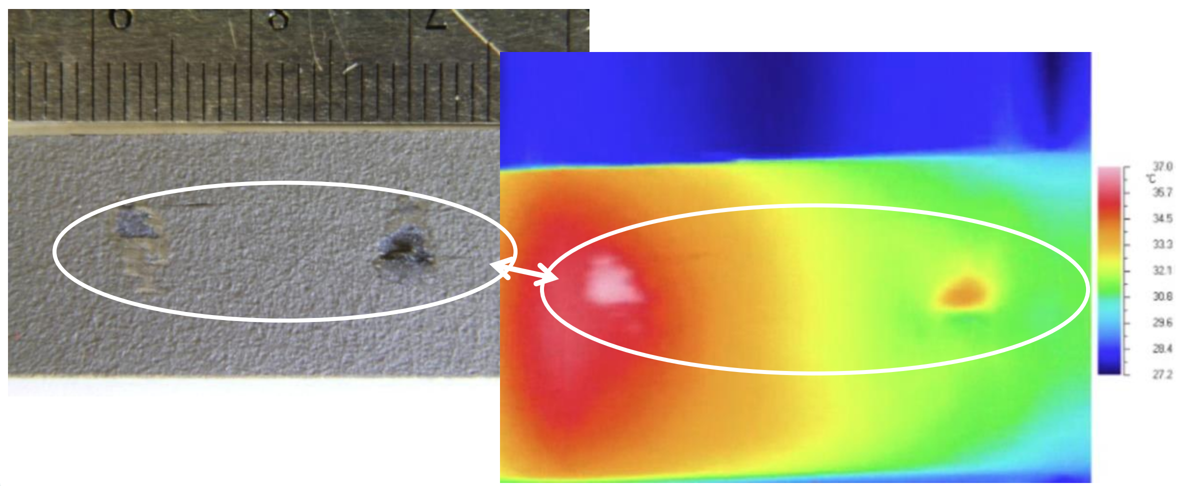
Investigating effects of manufacturing defects on MEA performance to understand the accuracy requirements for diagnostics

QC System



Example:

- DC excitation of catalyst coated membrane causes thermal response
- Defects alter catalyst layer resistance and thermal response
- IR camera provides rapid, quantifiable 2D data



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

BERKELEY LAB

GDL Fabrication Cost Reduction

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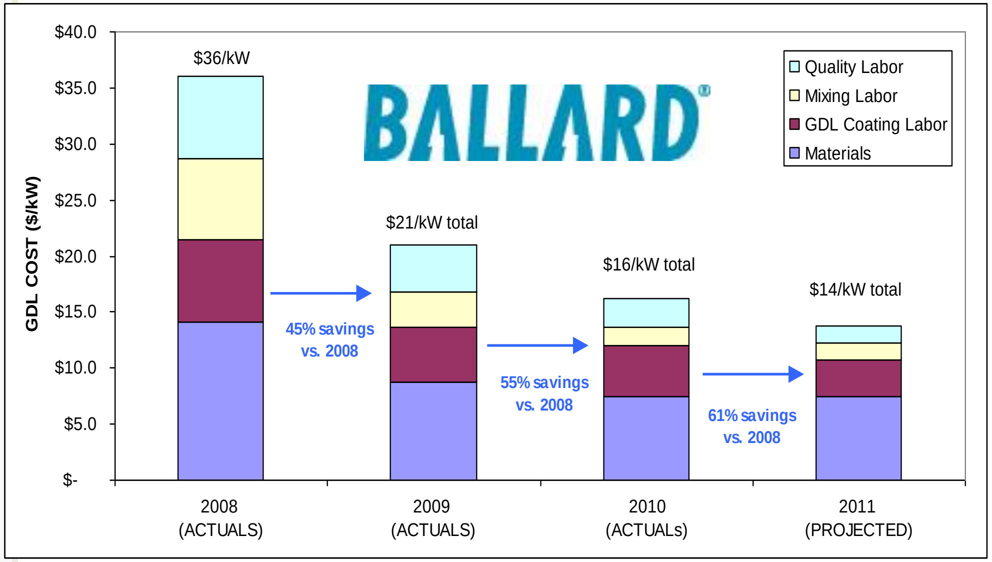
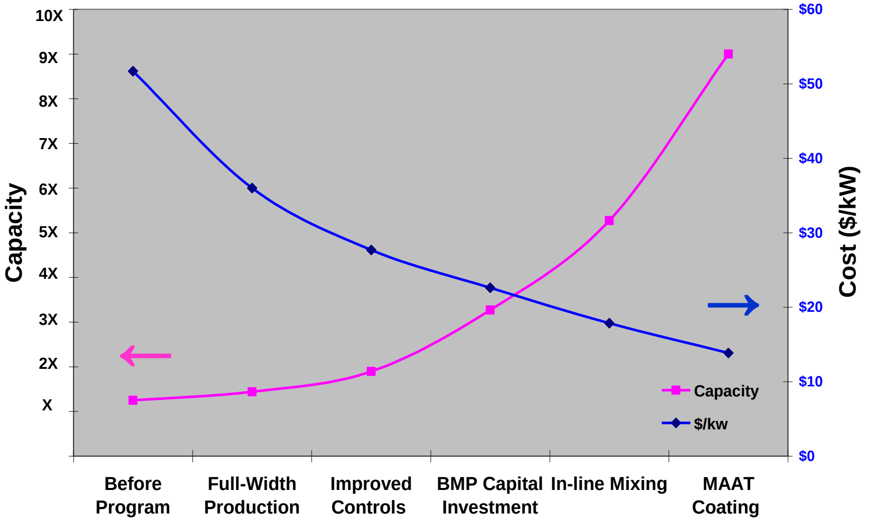
Reduced cost of GDLs by more than 50% and increased manufacturing capacity more than 4x since 2008

Project Approach:

- **Reduce high material & manufacturing costs:**
  - Eliminate process steps, improve production yields, reduce scrap and increase production efficiency
- **Develop high-volume MEA (GDL) processes:**
  - Process modifications introduced in this project have increased production volumes nearly 4-fold
- **Improve low levels of quality control and inflexible processes:**
  - Introduce new quality control technologies such as mass flow meters to control MPL loadings, provide more uniform properties and reduce the amount of ex situ testing required
  - Add an in-line visual inspection station as a final quality tool to improve processing efficiency and accuracy

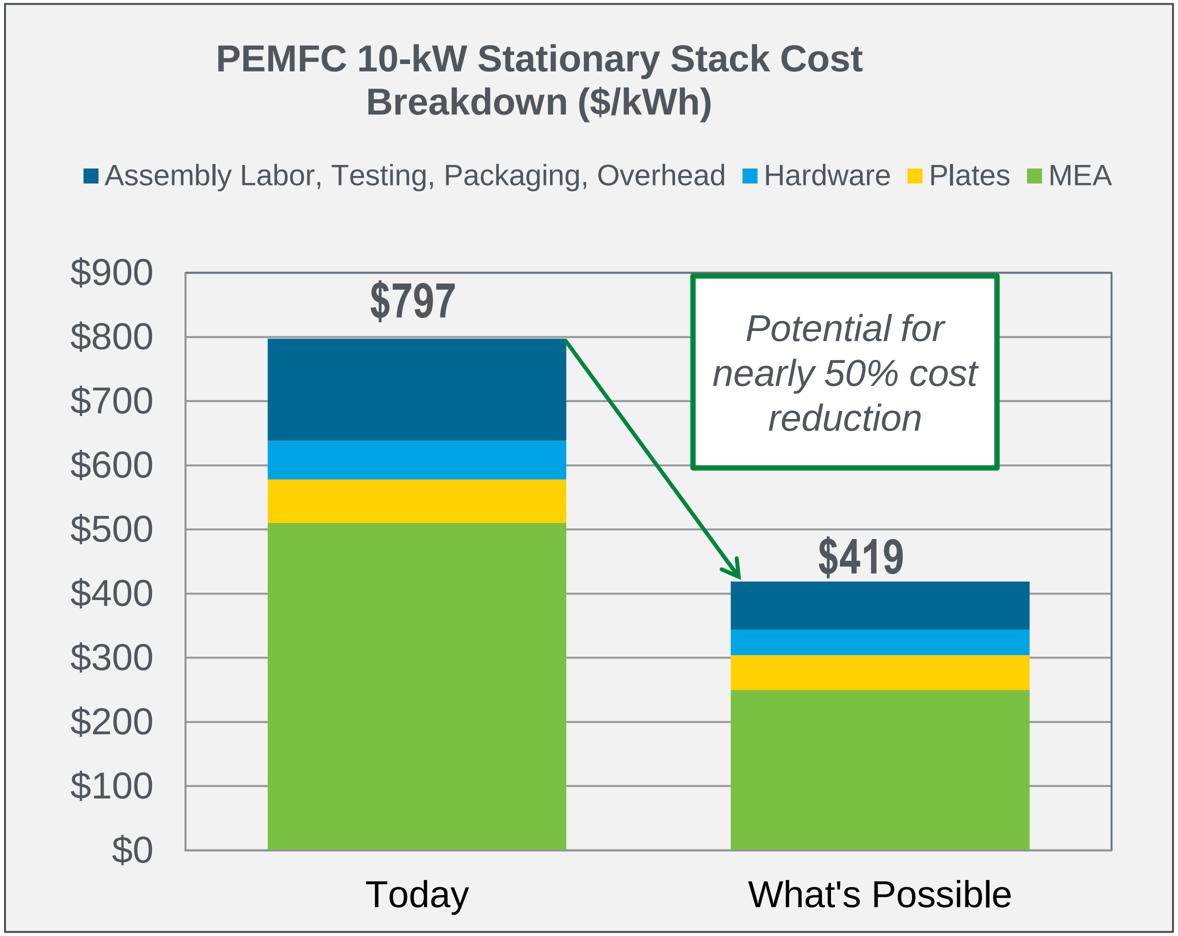




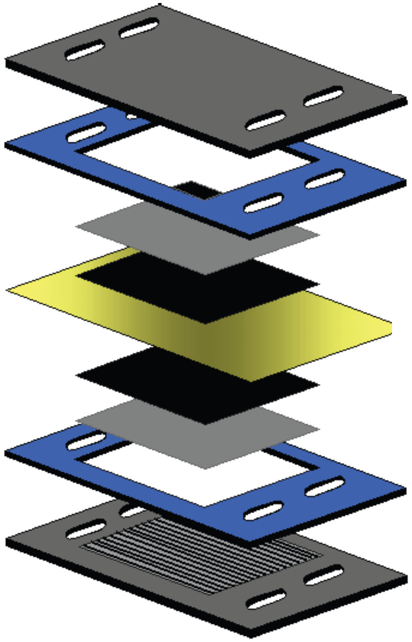
Example: Stationary FC Stack Cost Breakdown

Key Goals:

- **Automotive fuel cell systems: 5,000 hr durability, $30/kW (2017)**
- **µ-CHP fuel cell systems: 45% electrical efficiency, 60,000 hr durability, $1500/kW (2020)**



Source: Ballard



Membrane electrode assembly

Source: 3M

PEMFC Manufacturing: Status vs. Needs

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Status of current PEMFC manufacturing technology and potential effect of technology injection

Current		Advancements
MEA: • Decal transfer of electrode to membrane • Large batch mixing • Roll-to-roll processes for membrane, electrode, and GDL fabrication • Manual assembly of MEA with seals • Hot pressing	→	• Direct coating of electrode on membrane • Continuous mixing • Robotic or roll-to-roll assembly of MEAs with seals • Hot-roll lamination or improved pressing
Stack: • Manual assembly • Manual leak/performance test	→	• Automated assembly • Automatic leak/performance test
BOP: • Lean manufacturing cells and flow • Unique components	→	• Standardized designs • Robotic BOP/system assembly line

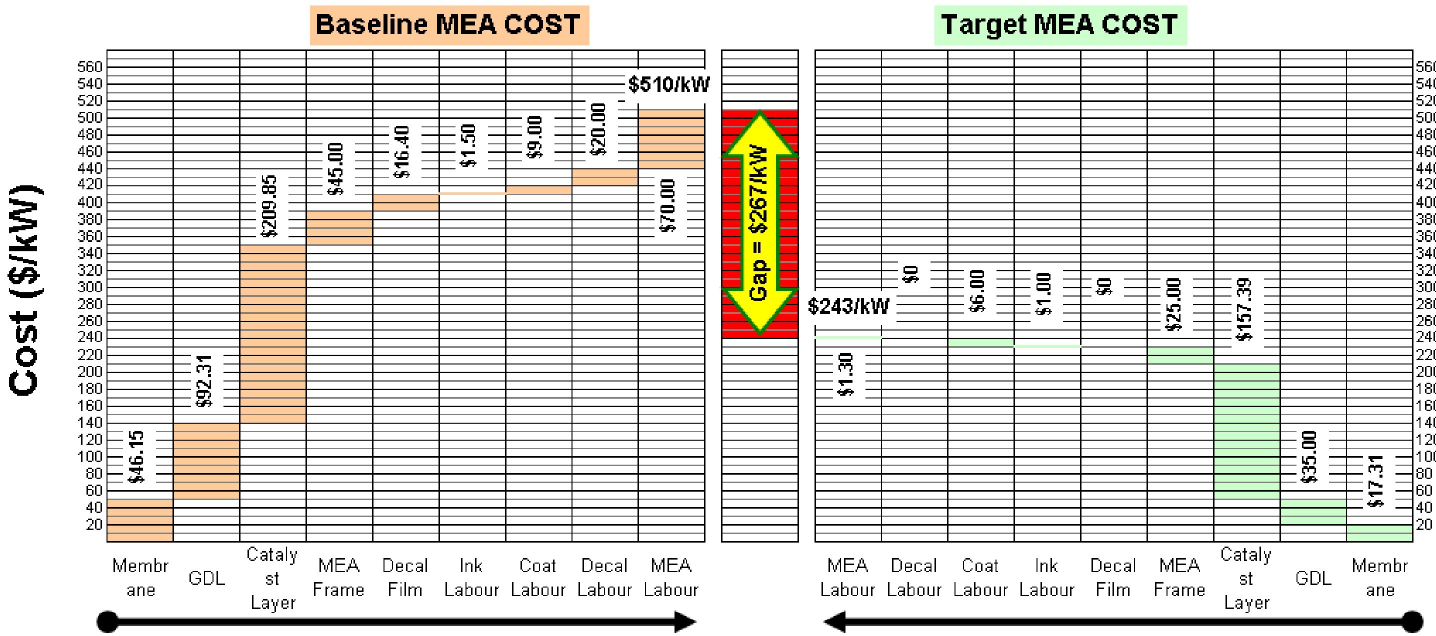
NREL PV-FC Collaboration

- Our success on the web-line convinced our PV group to construct and verify a conveyor-based platform for PV cells
  - Same line camera, encoder, software mods
- Now, they are developing a dual light source system that should improve accuracy
- When development is complete, will be integrated back into our motion-stage and web-line setups

Identify gaps in MEA manufacturing technology: How much better can we do?

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- The MEA was readily identified as the major cost driver in a 10 kW stationary stack.
- The precious metal catalyst electrode is the major cost driver for the MEA.



Baseline MEA Cost ($/kW) | **Target MEA Cost ($/kW)**

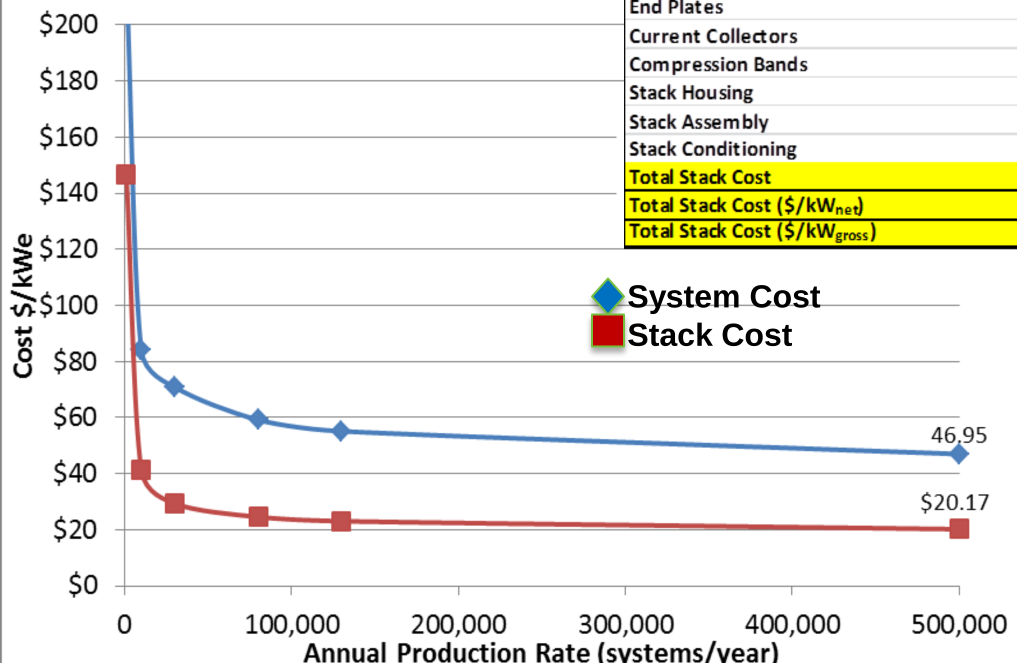
	Material Cost	Yield	Total Cost	Cost Gap	Total Cost	Yield	Material Cost	
Membrane	$27.69	60%	$46.15	$28.84	$17.31	80%	$13.85	Membrane
GDL	$55.39	60%	$92.31	$57.31	$35.00	80%	$28.00	GDL
Catalyst Layer	$125.91	60%	$209.85	$52.46	$157.39	80%	$125.91	Catalyst Layer
MEA Frame	$45.00	100%	$45.00	$20.00	$25.00	100%	$25.00	MEA Frame
Decal Transfer Film	$12.30	75%	$16.40	$16.40	$0.00		$0.00	Decal Transfer Film
Ink Mixing Labour			$1.50	$0.50	$1.00			Ink Mixing Labour
Coating Labour			$9.00	$3.00	$6.00			Coating Labour
Decal Transfer Labour			$20.00	$20.00	$0.00			Decal Transfer Labour
MEA Assembly Labour			$70.00	$68.70	$1.30			MEA Assembly Labour
		Total:	$510.21	$267.21	$243.00	Total		

Note: Cost reductions realized from both material price reduction and manufacturing yield improvements.

Source: Ballard

Major cost drivers for PEMFCs

Stack Cost and Total System Cost



Stack Component Cost

	2012 Automotive System					
Annual Production Rate	1,000	10,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80	80
System Gross Electric Power (Output)	88.24	88.24	88.24	88.24	88.24	88.24
Bipolar Plates (Stamped)	$1,819.33	$436.67	$411.17	$395.16	$395.55	$392.33
MEAs	$9,082.91	$2,623.29	$1,758.30	$1,415.04	$1,307.39	$1,103.35
Membranes	$3,518.73	$882.16	$495.01	$336.62	$276.84	$171.17
Catalyst Ink & Application (NSTF)	$1,452.68	$816.70	$770.79	$764.76	$763.42	$759.85
GDLs	$2,137.41	$638.84	$359.04	$214.65	$166.39	$82.09
M & E Hot Pressing	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
M & E Cutting & Slitting	$487.44	$50.71	$18.36	$8.24	$5.91	$3.15
MEA Frame/Gaskets	$1,486.64	$234.87	$115.10	$90.78	$94.83	$87.10
Coolant Gaskets (Laser Welding)	$212.59	$41.52	$28.59	$26.98	$26.60	$26.01
End Gaskets (Screen Printing)	$149.48	$15.04	$5.08	$1.97	$1.25	$0.53
End Plates	$96.65	$33.18	$29.35	$24.93	$22.55	$17.12
Current Collectors	$52.57	$11.40	$7.61	$5.74	$5.16	$4.53
Compression Bands	$10.00	$9.00	$8.00	$6.00	$5.50	$5.00
Stack Housing	$60.50	$60.50	$60.50	$60.50	$60.50	$60.50
Stack Assembly	$76.12	$59.00	$40.69	$34.95	$33.62	$32.06
Stack Conditioning	$170.88	$56.78	$53.87	$47.18	$41.38	$28.06
Total Stack Cost	$11,731.03	$3,296.20	$2,349.26	$1,963.46	$1,843.95	$1,613.36
Total Stack Cost ($/$kW_{net}$)	$146.64	$41.20	$29.37	$24.54	$23.05	$20.17
Total Stack Cost ($/$kW_{gross}$)	$132.94	$37.35	$26.62	$22.25	$20.90	$18.28

Major cost drivers at low volume include membranes, GDLs, bipolar plates, catalyst ink, and MEA frame/gaskets

Source: SA, Inc.

Cost of Manufacturing Machinery for Automotive FC systems

Source: DTI Automotive DFMA Task Report _Tasks 4 1 1-4 1 5_ FINAL.pdfDTI Automotive DFMA Task Report _Tasks 4 1 1-4 1 5

Stack Manufacturing Machinery Capital Costs			
Step	**Cost $/Process Train**	**No. of Process Trains**	**Capital Cost**
Bipolar Plate Stamping	$393,057	41	$16,115,331
Bipolar Plate Coating	$68,529,662	~20*	$68,529,662
Membrane Production	$30,000,000	1	$30,000,000
NSTF Coating	$1,284,255	12	$15,411,056
Microporous GDL Creation	$1,271,840	17	$21,621,283
M & E Hot Pressing	$187,542	37	$6,939,065
M & E Cutting & Slitting	$130,958	2	$261,917
MEA Frame/Gaskets	$598,772	154	$92,210,849
Coolant Gaskets (Laser Welding)	$789,955	32	$25,278,555
End Gaskets (Screen Printing)	$630,187	1	$630,187
End Plates	$333,760	3	$1,001,280
Current Collectors	$67,089	1	$67,089
Compression Bands	$521,983	2	$1,043,965
Stack Assembly	$799,418	51	$40,770,338
Stack Conditioning	$147,516	145	$21,389,879
Stack Total			**$341,270,457**

Progress – Manufacturing

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

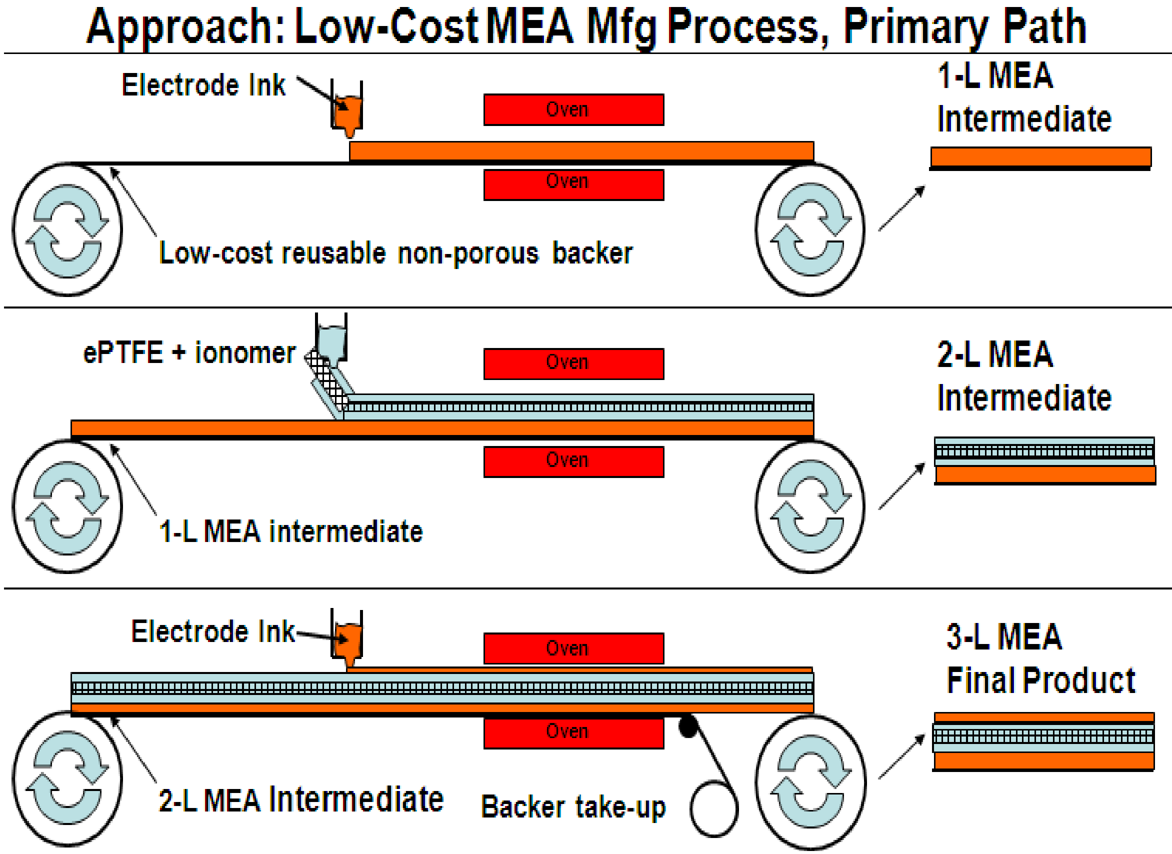
Increased performance by 200 mA/cm² at 0.4 V by improving the membrane/anode interface through direct coating

W. L. Gore increased performance and reduced MEA and stack cost

- Eliminated intermediate backer materials
- Reduced number of coating passes
- Minimized solvent use
- Reduced conditioning time

Enabling Technologies:

- Direct coating to form membrane–electrode interface
- Gore's ePTFE membrane reinforcement & PFSA ionomers enable durable, high-performance MEAs
- Modeling of mechanical stress and heat / water management
- Advanced fuel cell testing & diagnostics



Next Steps: Explore new 3-Layer MEA Process

- Equipment configuration for MEA production
- Raw material formulations
- Map process windows for each layer of the MEA